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Area determination of solar desalination system for irrigating crops in greenhouses using different quality feed water

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ABSTRACT

The aim of this study was to present an alternative means of procuring fresh water from low-quality water sources to meet crop-water requirements (CWR) in greenhouses. A solar still was used in field experiments to desalinate three types of water: seawater, ground water and agricultural-drainage water. Three multiple linear regression models were derived, with an average coefficient of determination (R^2) of 0.90 for the prediction of water-productivity capacity (MD). Two methods were used to estimate the CWR of greenhouses: the adapted Penman-Monteith (A-PM) method and the Fernandez (F) method. The R^2 for the two methods was 0.95. The three water-productivity measurements were compared with the water requirements throughout the year to determine the required area of the solar-desalination system. The results indicated that the A-PM method can be used to estimate the CWR of crops grown in greenhouses. Generally, MD exceeded CWR throughout the year, and the average MD of the water types was 4.79 L/m^2/day. In addition, the average CWR values obtained using the A-PM and F methods were identical (1.88 L/m^2/day). The water produced by 1 m^2 of the solar-still system was also found to meet the CWR of about 2 m^2 of greenhouse. As the system's MD exceeds the CWR of a greenhouse, the proposed solar-desalination system is clearly able to meet greenhouse CWR.

1. Introduction

The world is currently facing severe water-related problems, especially in arid regions, which will continue to worsen if no radical and effective solutions are found. In light of climate change, a growing population, an increasing demand for food and water and rising fuel prices, novel means of addressing water shortages are urgently required. Oron et al. (2008) stated that agricultural irrigation makes up approximately 60–90% of the world's total water consumption. However, the increasing demand for water, particularly in arid and semiarid regions, has forced farmers and other agricultural producers to use low-quality water sources such as seawater, brackish water and agricultural-drainage water for irrigation. Before such water can be used for irrigation, it must be treated and desalinated to prevent damage to crops, productivity and soil. Desalination is increasingly regarded as a valuable means of procuring water for drinking and agricultural irrigation (Ben-Gal et al., 2009; Greenlee et al., 2009). The rising economic and environmental costs of conventional energy sources have led researchers to investigate solar energy as a potential power source for desalination. Water desalination and production powered by solar energy may help to solve key problems related to the demand for irrigation water, especially for greenhouse crops.

Although solar-desalination systems such as solar stills cannot supply the quantity of water required to irrigate a crop grown in an open field, they may be able to provide sufficient water for protected cultivation in greenhouses. Solar stills can supply arid regions and remote areas with water in the absence of advanced technology and highly skilled personnel (Bouchekima, 2003). Such stills have low operation and maintenance costs, but incur high initial costs and require large areas of land (Bhattacharyya, 2013). The initial costs can be compensated by the production of cash crops with high economic returns. According to Zarzo et al. (2012), desalination provides a novel and additional water resource for agriculture and irrigation. Moreover, desalinated water is an inexhaustible resource; in the case of seawater desalination, for example, seawater never runs out. Greenhouses fitted with solar-desalination systems enable small-scale cultivation in regions in which only saline or brackish water is available (Malik et al., 1996).

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Although the distilled-water productivity of solar-desalination systems is insufficient to meet the crop-water requirements (CWR) of crops grown in open irrigated fields, such systems may be able to provide enough fresh water for protected cultivation in greenhouses (Kudish and Gale, 1986). As noted by Tiwari et al. (1992), the water consumption of crops in protected cultivation fluctuates diurnally and seasonally, similar to the variation in productivity of solar desalination. As both processes are driven primarily by solar radiation, which is variable, consumption and provision are closely correlated. In addition, the use of solar desalination enhances the water-use efficiency of crops in protected cultivation. If water-use efficiency is associated with the market price of vegetables, the income of small-scale growers will be increased, especially in regions with limited water resources (Abou Hadid et al., 2004).

Numerous studies of solar desalination and its application to greenhouse irrigation have been conducted. Trombe and Foex (1961) presented the first complete analysis of a system combining a solar still with a greenhouse, and improved versions were developed by Boutiere (1972) and Bettaque (1977). Hassan et al. (1989) proposed a multi-stage roof-integrated solar still. Fath (1994) presented an integrated greenhouse and solar-distillation system that was self-sufficient in energy and irrigation-water production. Paton and Davis (1996) developed a humidification dehumidification greenhouse integrated desalination unit capable of producing fresh water to support crop growth in arid regions near the sea. Chaibi (2000, 2002) used simulations and experiments to investigate a greenhouse roof integrated desalination system, and deduced that the system could be used as both a thermal screen and a means of supplying irrigation water to greenhouse crops in arid environments. Chaibi and Jilar (2003) integrated a solar still into the south slope of a greenhouse roof, and analyzed its operation. In environments in which only low-quality water, such as saline or brackish water, is available, greenhouses combined with solar stills may offer a valuable means of developing small-scale agriculture. Zhani (2013) performed a theoretical and experimental solar-desalination study at the National Engineering School of Sfax in Tunisia, and found that the high-quality distilled water obtained was favorable for drinking and irrigation purposes. Medina (2006) showed that the use of water desalination in agriculture is technically feasible, and that the required technology is available. According to Ghermandi and Messalem (2009), the volume of desalinated water intended for agricultural irrigation in countries such as Palestine and the United Arab Emirates has significantly increased in recent years. In arid environments, protected cultivation in greenhouses not only provides a suitable environment for crop growth, but decreases CWR by reducing reference evapotranspiration (*ETo*). Montero et al. (1985) and Rosenberg et al. (1989) stated that approximately 20–40% less evapotranspiration (ET) takes place inside a greenhouse than in an open field. Similarly, Farias et al. (1994) found that ET is consistently lower in greenhouses than in open fields, with a reduction in ET of approximately 23–55%. Braga and Klar (2000) obtained greenhouse *ETo* values that were 20–25% smaller than the equivalent open-field values. Fernandes et al. (2003) found that greenhouses decreased *ETo* by 60–85% compared with open fields. All of these findings indicate that greenhouse cultivation requires substantially less water than open-field agriculture. Therefore, protected cultivation in greenhouses increases the water-use efficiency of crops. In addition, Stanghellini (1993) stated that greenhouse agriculture decreases *ETo* to about 70% of its equivalent open-field value, thus improving the use of water relative to unprotected cultivation. Harmanto et al. (2005) studied the water requirements of drip-irrigated tomatoes grown in greenhouses in a tropical environment. They found that a greenhouse farming system performed better than an open farming system in terms of crop yield, irrigation-water productivity and fruit quality. Crop evapotranspiration (*ETc*) inside the greenhouse was found to be 75–80% of the open-field *ETc*, calculated with the same climatic parameters. Radhwan (2004) also noted that the irrigation-water requirements of greenhouses are only 10% of those in the open field. Möller et al. (2004) reported a 60% reduction in CWR inside a screened greenhouse, relative to the external environment. As noted by Perret et al. (2005), the plastic cover of a greenhouse acts as a barrier against moisture loss, reducing *ETo* by as much as 60–85% compared with its value in an open field.

It is clear from the findings reported above that the efficacy of solar desalination in meeting CWR in greenhouses has not previously been addressed by researchers. Therefore, the objectives of this study are as follows: (1) to predict water-productivity capacity (MD) using a multiple linear regression approach, (2) to compare the accuracy of the adapted Penman-Monteith (A-PM) and Fernandez (F) methods in estimating CWR, (3) to ascertain whether the MD of solar desalination is sufficient to meet CWR and (4) to determine the total surface area of the solar-desalination system (A) required to meet the water requirements of different crops grown in a greenhouse environment.

2. Materials and methods

Two computational methods were used to calculate CWR: the A-PM method and the F method. The MD of the solar-desalination system was estimated for three types of water. Next, CWR and MD were compared to determine the area required to meet the CWR of greenhouses. The methodology is illustrated in a simple diagram in Fig. 1.

2.1. Experiment setup and data used

The experiments were conducted at the Agricultural Research and Experiment Station at the Department of Agricultural Engineering, King Saud University, Riyadh, Saudi Arabia (24°44′10.90″ N, 46°37′13.77″ E) between February and November 2013. The weather data were obtained from a weather station (model: Vantage Pro2; manufacturer: Davis, USA) close to the experimental site (24°44′12.15″ N, 46°37′14.97″ E). The solar-still system used in the experiments was constructed from a 6 m^2 single stage C6000 panel (F Cubed. Ltd., Carocell Solar Panel, Australia). The solar-still panel was manufactured using modern, cost-effective materials such as coated polycarbonate plastic. When heated, the panel distilled a film of water that flowed over the absorber mat of the panel. The panel was fixed at an angle of 29° from the horizontal plane. The basic construction materials were galvanized steel legs, an aluminum frame and polycarbonate covers. The transparent polycarbonate was coated on the inside with a special material to prevent fogging (patented by F Cubed, Australia). Front and cross-sectional views of the solar still are presented in Fig. 2.

The water was fed to the panel using a centrifugal pump (model: PKm 60, 0.5 HP, Pedrollo, Italy) with a constant flow rate of 10.74 L/h. The feed was supplied by eight drippers/nozzles, creating a film of water that flowed over the absorbent mat. Underneath the absorbent mat was an aluminum screen that helped to distribute the water across the mat. Beneath the aluminum screen was an aluminum plate. Aluminum was chosen for its hydrophilic properties, to assist in the even distribution of the sprayed water. Water flowed through and over the absorbent mat, and solar energy was absorbed and partially collected inside the panel; as a result, the water was heated and hot air circulated naturally within the panel. First, the hot air flowed toward the top of the panel, then reversed its direction to approach the bottom of the panel. During this process of circulation, the humid air touched the cold surfaces of the transparent polycarbonate cover and the bottom polycarbonate

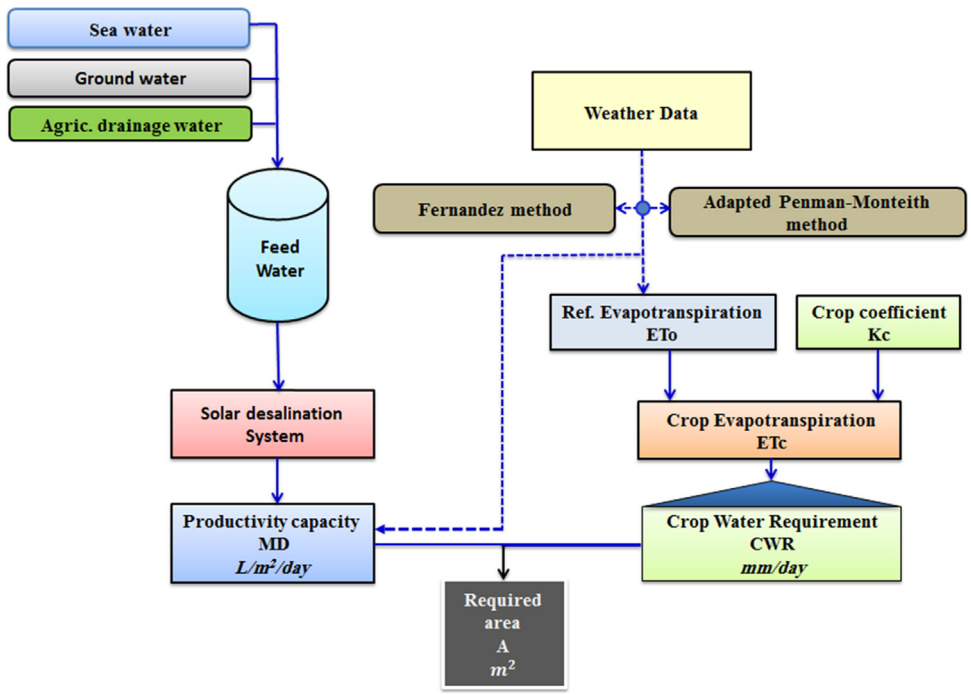

Fig. 1. Flow chart of the calculation of the solar system area required (*A*) to meet crop water requirement (CWR).

layer, causing condensation. The condensed water flowed down the panel and was collected in the form of a distilled stream. Three feed-water sources were used as inputs to the system: seawater, ground water and agricultural-drainage water. The system was run with seawater from 02/23/2013 to 04/23/2013, with ground water from 05/31/2013 to 09/20/2013 and with agricultural-drainage water from 10/05/2013 to 11/01/2013. Raw seawater was obtained from the Gulf, Dammam, in eastern Saudi Arabia (26°26′24.19″ N, 50°10′20.38″ E). Raw ground water, a reject product of ground water treatment plants, was obtained from Bouwaib Station, east of Riyadh, the capital of Saudi Arabia (25°6′58.36″ N, 46°50′28.49″ E). Raw agricultural drainage water was obtained from Al-Oyun City, Al-Ahsa, in eastern Saudi Arabia (25°35′7.02″ N, 49°35′48.17″ E). The initial concentrations of total dissolved solids (TDS) in the three types of water, along with their pH, density (ρ) and electrical conductivity (EC), are listed in Table 1. TDS concentration and EC were measured using a TDS-calibrated meter (Cole-Parmer Instrument Co. Ltd., Vernon Hills, USA). A pH meter (model: 3510 pH meter; Jenway, UK) was used to measure pH. A digital-density meter (model: DMA 35_N, Anton Paar, USA) was used to measure ρ. The three inputs were fed separately to the panel using the pump described above. The residence time—the time taken for the water to pass through the panel—was approximately 20 min. Therefore, the flow rate of the feed water, the distilled water and the brine water was measured every 20 min. A simple sketch of the solar-desalination system is provided in Fig. 3.

Table 1
Some properties of the sea water, ground water and agricultural drainage water used for desalination process.

Property	Sea water	Ground water	Drainage water
TDS ($g\,L^{-1}$)	41.1	7.45	4.71
pH	8.02	8.1	8.1
ρ ($g\,cm^{-3}$)	1.04	1.01	1.001
EC ($mS\,cm^{-1}$)	66.34	11.93	7.54

The weather data, such as air temperature (*To*), relative humidity (RH), wind speed (*U*), solar radiation (*Rs*) and ultraviolet index (UVI), were obtained from a weather station near the experimental site. MD, or the amount of distilled water produced by the system in a given time, was obtained by collecting and measuring the amount of water cumulatively produced over time. All of the statistical analysis and data processing were carried out using IBM's Statistical Package for the Social Sciences Statistics 21 (SPSS Inc., Chicago, IL, USA). Stepwise linear regression analysis was used to find a reasonable set of empirical equations, with constants significant at the 5% level. The experiments involved one dependent variable (the MD of the solar-desalination system) and five independent variables (UVI, *Rs*, *To*, RH and U). Multiple linear regression models were developed from the experimental data to predict MD. The weather data used to compute *ETo* and MD, which comprised about 4 years' worth of observations in the Riyadh region from 2010 to the end of 2013, were taken from the abovementioned weather station. Based on these data, *ETo* was calculated and MD was predicted. The values of *To*, RH, U, *Rs* and UVI ranged from 2.95–47.3 °C, 2.18–88%, 0–12.9 km/h, 0–931.95 W/m^2 and 0–7.7, respectively. For illustration, Fig. 4 shows the distribution of the daily average values of *Rs* and UVI throughout the year. Notably, *Rs* and UVI were found to fluctuate in harmony with each other during the year. The overall average values of *Rs* and UVI were found to be high in the spring and summer. The fluctuations in *Rs* and UVI were due to meteorological instability during the year. Precipitation was also found to be a very important determinant of the performance of the solar-desalination system. It strongly influenced *Rs*, the desalination process and the MD of the system. A descriptive plot of the average monthly rainfall recorded between 2010 and 2013 is provided in Fig. 5. The average annual precipitation was 63 mm, of which 44.55% took place between March and April and 25.71% in November. The remaining precipitation comprised 7.4 mm (11.75%), 0.8 mm (1.72%), 2.6 (4.13%), 4.2 mm (6.67%) and 3.73 mm (5.93%) in January, February, May, October and December, respectively. Finally, almost no precipitation was observed in the summer.

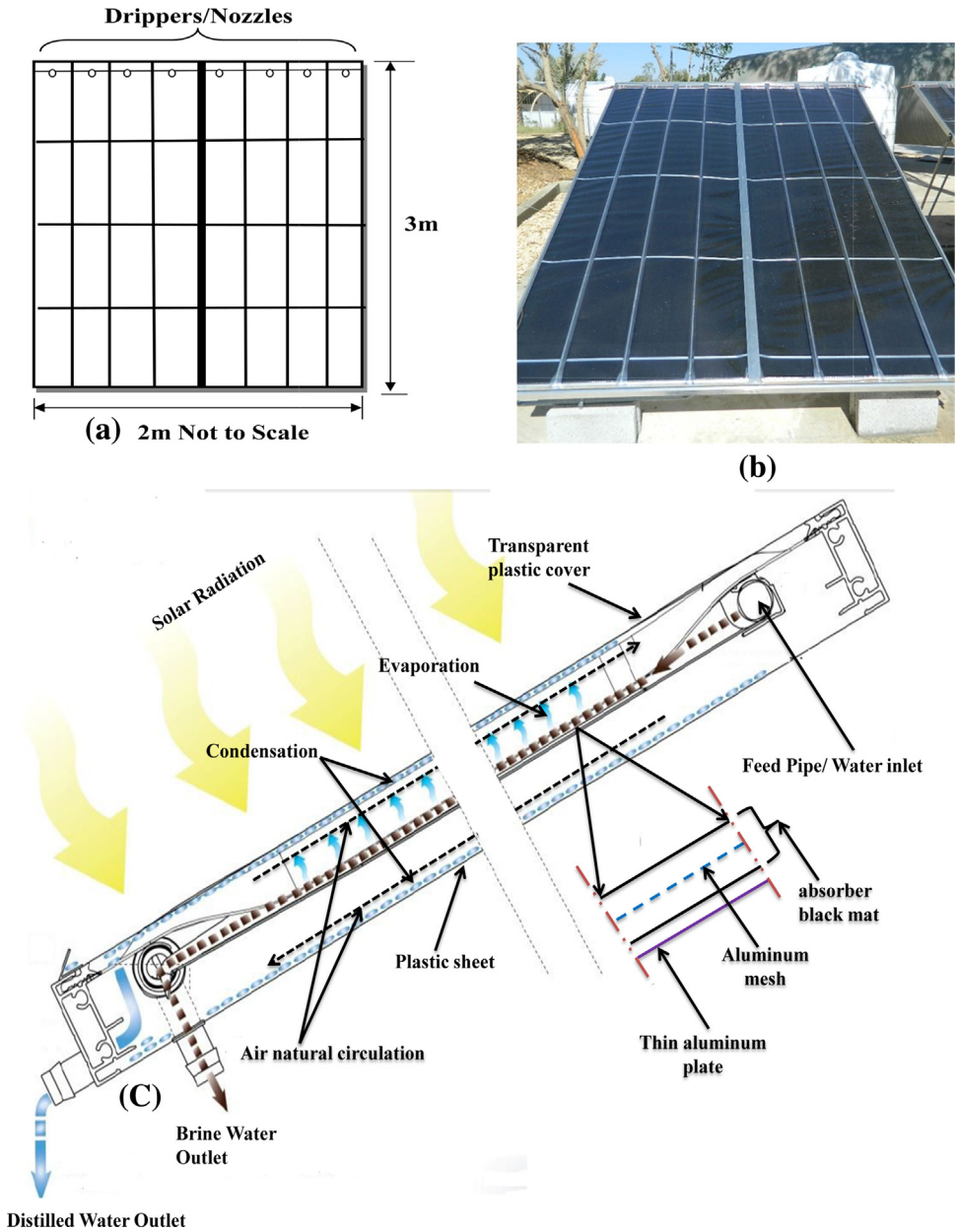

Fig. 2. Solar still panel: front section (a), picture of the panel (b) and cross sectional view of the solar still panel (c).

2.2. CWR calculation

The CWR for each of the greenhouse crop coefficients were calculated in four steps, as follows.

First step: calculation of *ETo*.

As previously mentioned, two methods were used to compute the *ETo*: the A-PM method and the F method.

2.3. A-PM methodology

The term "CWR" was defined by Allen et al. (1998) as the "amount of water required to compensate the evapotranspiration loss from the cropped field." Many mathematical models have been developed to estimate ET. The United Nations Food and Agricultural Organization (FAO) has recommended that the FAO-56 PM method be used in open-field conditions (Allen et al., 1998). The FAO-56 PM model is formulated as follows (Allen et al., 1998):

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

In the above, *ETo* is given in mm/day; Δ is the saturation slope vapor pressure curve (kPa/°C); R_n is the net radiation at the grass surface (MJ/m^2/day); G is the soil-heat flux (MJ/m^2/day); c is the psychometric constant (kPa/°C); U_2 is the mean daily wind speed at a height of 2 m (m/s); T is the mean daily air temperature (°C); e_s is the air saturation vapor pressure (kPa); and e_a is the actual vapor pressure (kPa). R_n and G were estimated using the procedure described in the FAO's Manual 56 (Allen et al., 1998).

According to Von Zabeltitz (2011), the FAO-56 PM model can be used with greenhouses if its parameters are adapted to greenhouse climate conditions. The temperature inside an unheated greenhouse is generally higher than the temperature outside, but the

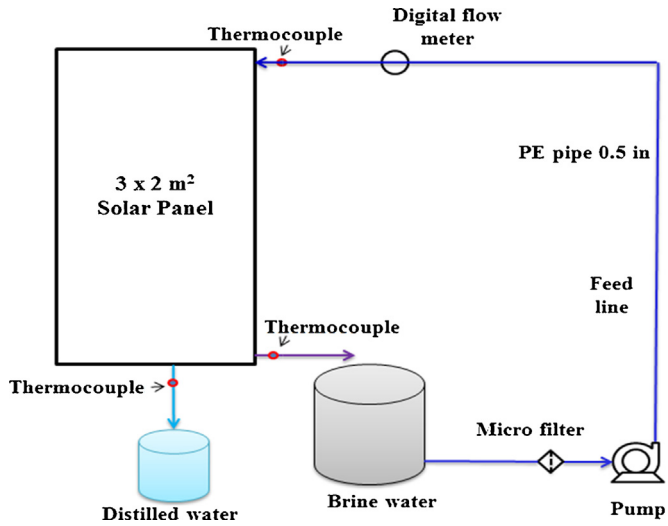

Fig. 3. Simple sketch of the experiment setup.

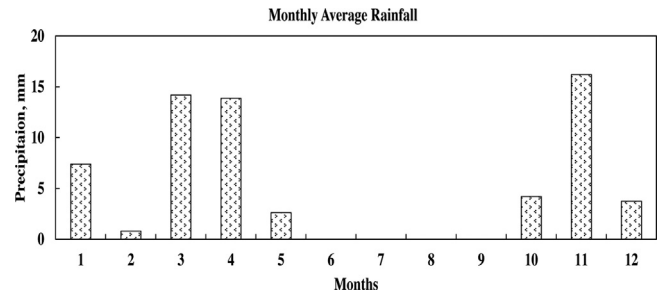

Fig. 5. Histogram of average monthly rainfall (in mm).

greenhouse receives less incoming global radiation than its external environment. These factors must be taken into account when calculating ET in greenhouses. In winter, the average temperature inside a well-ventilated greenhouse during the daytime is approximately 4 °C higher than the outside temperature (Thomas, 1994; Von Zabeltitz, 1986; Rath, 1994). The average temperature inside an unheated greenhouse at night is approximately 2 °C higher than the temperature outside, due to the heat stored by the greenhouse soil. Therefore, the minimum and maximum temperatures inside a greenhouse (T_{mini} and T_{maxi}) can be calculated as follows:

$$T_{maxi} = T_{maxo} + 4 \quad (2)$$

$$T_{mini} = T_{mino} + 2 \quad (3)$$

where T_{mino} and T_{maxo} are the minimum and maximum temperatures outside the greenhouse. The mean temperature inside the greenhouse can thus be calculated as follows:

$$T_{meani} = \frac{T_{maxi} + T_{mini}}{2} \quad (4)$$

In summer, greenhouses are cooled and their temperature is maintained at approximately 30 °C to ensure optimal plant growth. According to Fath and Zakaria (2004), the basic comfort values for greenhouse planting are as follows: a temperature of 10–30 °C, a relative humidity of 25–80% and an air velocity of 0.1–0.25 m/s (0.5 m/s maximum).

External RH decreases as external temperature increases during the day. However, due to continuous ET from the plants and soil, the RH inside a greenhouse remains relatively high, even if the greenhouse is ventilated during the daytime. The average daytime RH inside a ventilated greenhouse can be as high as 75–80%. The incoming global radiation is decreased by the cladding material and construction components (Von Zabeltitz, 2011), and can be formulated as follows:

$$Rs_i = Rs \times \tau, \quad (5)$$

where τ is the transmittance of the greenhouse (0.6–0.7 for single plastic film covered greenhouses) (Von Zabeltitz, 2011) and Rs is the external global radiation.

2.4. F methodology

Fernandez et al. (2009) proposed the following formula for computing ETo in an unheated greenhouse.

$$\text{Julian days (JD)} \geq 220 \quad ETo = (0.288 + 0.0019\text{JD})Rs_i \quad (6)$$

$$\text{Julian days (JD)} < 220 \quad ETo = (1.339 - 0.00288\text{JD})Rs_i \quad (7)$$

This equation is based on measurements of daily solar radiation outside the greenhouse, greenhouse transmissivity (Rs_i) and day of the year.

Second step: calculation of crop coefficient (Kc).

The Kc values were obtained from Allen et al. (1998). These values, which represent Kc at different stages for general vegetable crops, were 0.4 (minimum), 0.6 and 0.8 (average) and 1.05 (maximum).

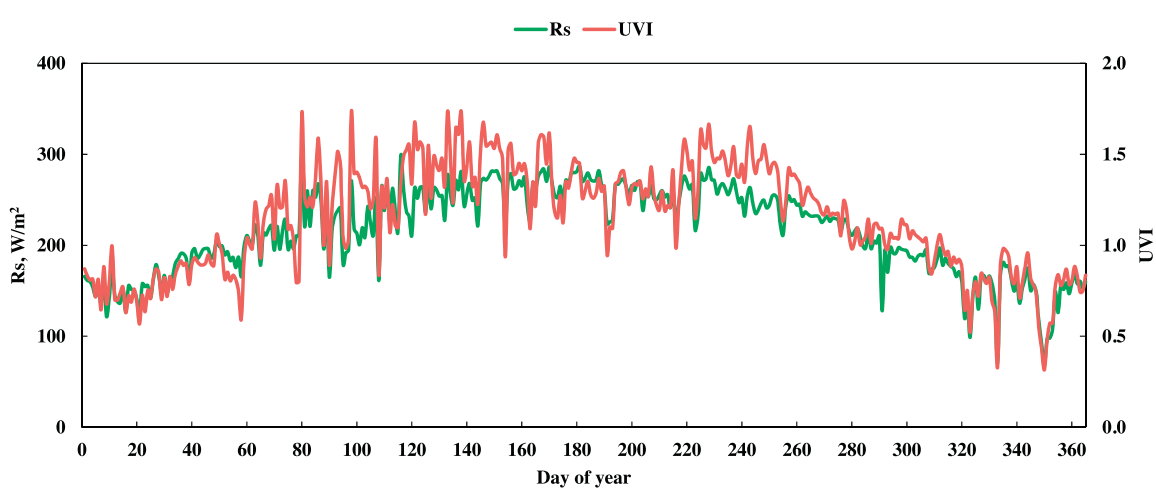

Fig. 4. The distribution of daily average solar radiation (Rs) and ultra violet index (UVI) throughout the year.

Table 2
The weather parameter ranges used in water productivity prediction models.

	Sea water	Ground water	Drainage water
To (°C)	16.87–33.23	34.72–43.75	24.30–39.36
RH (%)	12.90–70.00	2.14–12.00	7.81–30.19
U (km/h)	0.00–12.65	0.00–8.43	0.00–5.18
Rs (W/m^2)	75.10–920.69	271.52–909.81	223.19–810.05
UVI (–)	0.00–6.00	0.78–7.42	0.48–5.53

Third step: calculation of *ETc*.

$$ETc = ETo \times Kc \tag{8}$$

Fourth step: calculation of CWR.

The daily CWR, CWR_d, can be estimated as follows (Von Zabeltitz, 2011):

$$CWR_d = ETc(1 + l_i) \times \frac{A_{Crop}}{A_G} \tag{9}$$

where l_i is the loss factor for irrigation (0.03–0.1 for drip-irrigation systems) and A_{Crop}/A_G is the ratio of the crop-covered area to the greenhouse-floor area (0.9 for vegetables and cut flowers in ground beds).

3. Results and discussion

In this section, the MD values for different types of water, the *ETo* values calculated by the A-PM and F methods and the monthly values of MD and *ETo* are compared. In addition, the MD and A of the solar-desalination system are calculated.

3.1. Comparison of system MD for seawater, ground water and agricultural-drainage water

According to the initial results of the field experiments, the overall performance of the solar-desalination system was as follows. The average MD for the three types of water was 0.51 L/m^2/h (approximately 5 L/m^2/day). This is consistent with the findings of Kabeel et al. (2012) and Radhwan (2004). The average operational recovery ratio and thermal efficiency were 34% and 51%, respectively. In addition, the average final recovery ratio for the three types of water was 86%.

MD was predicted using models obtained from the regression analysis of solar-desalination experiments using only meteorological parameters. The models were applicable within the ranges of independent variables listed in Table 2. As shown in Table 2, the average experimental values of *To*, RH, U, *Rs* and UVI for the three types of water were 32.1 °C, 22.51%, 4.38 km/h, 535.1 W/m^2 and 3.37, respectively. Approximately 10.56%, 19.88%, 0.03%, 1.68% and 0.03% of the data points for *To*, RH, *U*, *Rs* and UVI, respectively, did not fall within the prediction ranges for the three types of water. However, as these values were within their respective ranges for the whole of the year, the models derived are applicable year-round. The models are given below.

Seawater

$$MD = 0.543 - 0.015To - 0.042U - 0.006RH + 0.056UVI + 0.001Rs \tag{10}$$

Ground water

$$MD = 0.259 - 0.011To - 0.010U - 0.006RH + 0.025UVI + 0.001Rs \tag{11}$$

Drainage water

$$MD = 0.702 + 0.015To + 0.006RH + 0.053UVI + 0.001Rs \tag{12}$$

Table 3
Statistical parameters for the statistical models of productivity capacity using three types of water.

Model	R^2	RMSE (L/m^2/h)
Sea water	0.812	0.199
Ground water	0.962	0.042
Drainage water	0.920	0.151

The coefficient of determination (R^2) and root mean square error (RMSE) between the real and predicted MD of the solar-desalination system for the three types of water are presented in Table 3. The R^2 and RMSE for all three types of water were 0.90 and 0.131 L/m^2/h. The high R^2 and low RMSE values indicate a high level of model accuracy and good agreement between the real and predicted data. The regression models also indicated the significance of all of the parameters under study at the 0.05 level. *Rs* and UVI were generally found to be the most influential parameters; both had clear positive effects on the amount of water produced by the system. *To*, *U* and RH were found to have a negative influence on MD. The results of the agricultural drainage water model indicated that *Rs*, UVI, *To* and RH all had a strong positive influence on MD, which may be due to the absence of the effect of *U* in the drainage-water model. As previously mentioned, the statistical models were developed solely on the basis of weather parameters. In Fig. 6, the MD values for seawater, ground water and agricultural-drainage water are compared. Ground water yielded the lowest MD, except at the beginning and end of the year, when its MD values were similar to those of drainage water. However, the MD yielded by drainage water was almost the highest in summer. Midway through the year, the MD for seawater fell between the values for drainage water and ground water, but exceeded both at the beginning and end of the year. The average annual MD for both seawater and agricultural-drainage water was approximately 5 L/m^2/day, and approximately 4 L/m^2/day for ground water. As previously noted, this difference may be due to the sole use of meteorological parameters and the use of a separate set of experimental data in each model, leading to differences in model conditions. As the experiments were conducted in almost all seasonal weather conditions, the models are applicable year-round. Collectively, the maximum, average and minimum MD values for the three types of water were 8.42 L/m^2/day, 4.79 L/m^2/day and 0.85 L/m^2/day, respectively.

3.2. Comparison of efficacy of A-PM and F methods in calculating ETo

Fig. 7 depicts *ETo* calculated throughout the year using the A-PM method and the F method. The figure also illustrates the agreement between the values of *ETo* computed using the A-PM and F equations. It is clear from the figure that the results of the two methods were almost identical for certain days, and exhibited a high level of convergence for the remainder of the year. However, the values calculated by the A-PM method exceeded those produced by the F method for the majority of the year; the F method gave higher values only in June, July, August and September. These findings may be due to evaporative cooling, which is used in greenhouses in summer months to ensure that their heat and humidity conditions remain favorable for crop cultivation. As the A-PM equation reflects the conditions inside a greenhouse, evaporative cooling has a clear effect on the *ETo* values calculated by the A-PM method, unlike the F method, whose equation incorporates only the effects of solar radiation, greenhouse solar transmittance and Julian day. In Fig. 8, the estimated values of *ETo* using the A-PM method and the F method are compared. Despite slight deviation, the 1:1 line in Fig. 8 clearly indicates that the two sets of values were in general agreement. In other words, most of the data were fairly narrowly distributed

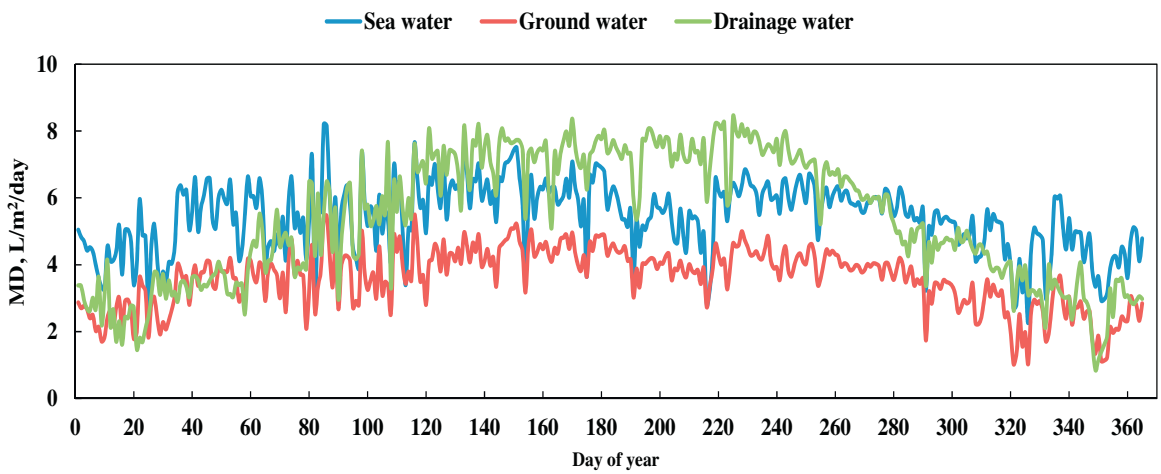

Fig. 6. Comparison of productivity capacity (MD) of the different types of water throughout the year.

around the 1:1 line. This high level of agreement is clearly reflected in the values of statistical parameters such as R^2 and RMSE (0.95 and 0.39 mm/day, respectively).

3.3. Comparison of monthly values of MD and ETo

Fig. 9 provides a histogram of the distribution of the monthly values of MD and *ETo* for the three types of water (seawater, ground water and agricultural-drainage water) using the A-PM method and the F method. Months are measured along the *x*-axis, and the *y*-axis indicates the MD of each of the three sources of water (mm/month) and the values of *ETo* obtained using the two methods (L/m^2/month). Using both the A-PM method and the F method, the monthly MD values of the three sources of water clearly exceeded the *ETo* values throughout the year, with only one exception: the MD for ground water in July calculated using the F method was slightly smaller than the *ETo*. The average (AVG), standard deviation (STDEV) and coefficient of variation (CV) were 145.60 L/m^2/month, 45.30 L/m^2/month and 0.311, respectively, for all of the MD data. The greatest MD (234.42 L/m^2) was achieved in August using agricultural-drainage water. The smallest MD, 74.64 L/m^2, was observed with ground water in December. MD consistently exceeded *ETo*, strongly supporting the hypothesis that solar desalination provides sufficient MD to meet the CWR of greenhouses.

3.4. MD and A of solar-desalination system required to meet CWR

Fig. 10 illustrates the MD and A of the solar-desalination system for seawater and different *Kc* values throughout the year calculated using the A-PM method and the F method, respectively. The MD reached its maximum value of 8 L/m^2/day at roughly the end of March, and fell to its lowest value of 2 L/m^2/day at the end of November. The average annual MD was 5.41 L/m^2/day. As shown in Fig. 10, which displays the overall results of the A-PM method, A gradually increased from the beginning of the year, reaching its maximum value approximately midway through the year, and then decreased until the end of the year. This trend was observed for both methods and all values of *Kc*. *Kc* and *A* were directly proportional; an increase in *Kc* increased the value of *A* required to meet CWR, and vice versa. This finding was consistent between the two methods. The required *A* was consistently less than 0.4 m^2/day for *Kc* values of 0.4 and 0.6, and only rarely exceeded 0.4 m^2 for a *Kc* value of 0.8. When *Kc* was 0.8, A reached its maximum values in August (0.89 m^2/day and 1.04 m^2/day with the A-PM method and the F method, respectively). Using both methods, a *Kc* of 1.05 produced a high value of *A*; however, this value was higher when calculated using the F method. The required-area curves were found to steepen dramatically at certain times of the year for both methods, primarily due to sudden weather changes at the beginnings and ends of seasons. Rainfall was found to be another determinant of A.

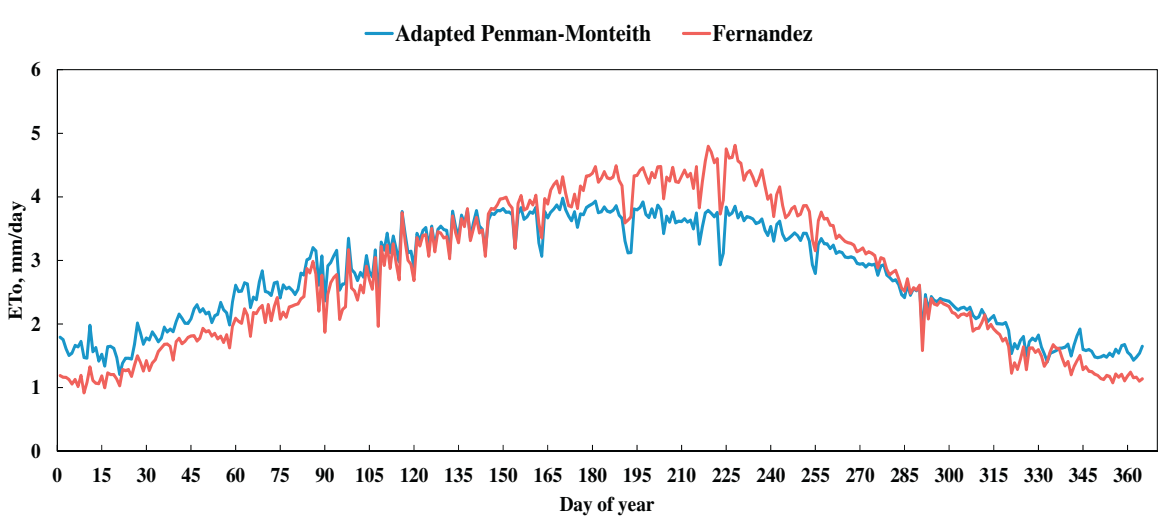

Fig. 7. Reference evapotranspiration (*ETo*) throughout the year with adapted Penman-Monteith method and Fernandez method.

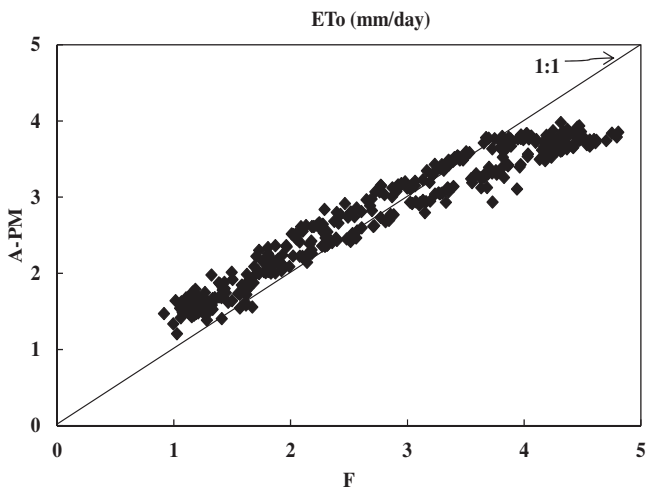

Fig. 8. Reference evapotranspiration (*ETo*) with Adapted Penman-Monteith method (A-PM) versus *ETo* with Fernandez method (F).

The rainfall from March to the end of May was 30.7 mm, approximately 49% of the annual rainfall. From November to December, the rainfall was 20 mm, 32% of the annual rainfall. An increase in required A indicates a decrease in MD, which may be due to the adverse effects of cloud cover on *Rs* and UVI. These variables certainly affect MD and the thermal behavior of the system as a whole. In general, this is also the trend with ground water and drainage water.

3.4.1. Numerical examples

In Table 4, the two methods of calculating CWR with seawater, ground water, and agricultural-drainage water are numerically compared, using 1 day (May 19) as an example. The table summarizes the *ETo*, *Kc*, *ETc*, CWR and A values for the three types of water as calculated separately by the A-PM and F methods. For the three types of water, the AVG, STDEV and CV of MD were 5.61 L/m^2/day, 1.51 L/m^2/day and 0.27, respectively. To a certain extent, smaller STDEV and CV values reflect greater agreement between the MD values for different types of water. The AVG, STDEV and CV of *ETo* using the A-PM and F methods were 3.33 mm/day, 0.0283 mm/day and 0.0085, respectively. The significantly small values of STDEV and CV indicate that the two methods were consistent in their calculation of *ETo*. The *ETo*, *ETc* and CWR values calculated using the A-PM method were slightly larger than their equivalent values using the F method. There was a high level of agreement between the A-PM and F estimates of the values of A required to meet CWR. For seawater, the R^2 and RMSE between the A values calculated by the two methods were 1.00 and 0.00707 m^2/day, respectively. Similar findings were obtained for ground water and agricultural-drainage water: the R^2 and RMSE between the two A values were respectively 1.00 and 0.00866 m^2/day for ground water, and 1.00 and 0.00707 m^2/day for agricultural-drainage water.

3.5. Preliminary cost estimate

Generally, the use of solar desalination in protected-agriculture contexts reduces fossil-fuel consumption and pollution, as well as the cost of treating this pollution. Moreover, solar desalination produces high-quality water, enabling the production of high-quality crops and thus increasing economic returns. The environmental conditions of a greenhouse cultivation system should be fully controlled, with mulching, hydroponics or aeroponics used to minimize water loss. However, the high economic returns of high-value horticultural cash crops (vegetables and flowers) can compensate for the system's operating costs. In this part of the study, numerical examples are provided to illustrate the amount of water and system area required to meet the CWR of greenhouses at peak *Kc* values. As economic factors play an important role in decision making, it is important to predict the cost of the system prior to its implementation in the field. The cost estimate also provides information on the feasibility of the system. In the following, the system costs required to meet the CWR of both a commercial greenhouse and a private greenhouse are estimated.

Numerical example (design parameters)

Feed-water tank = 35 l

In our case, area available for solar-desalination system = 6 m^2

Average recovery ratio = 0.86

Pumping cost = 267 USD (=1000 SAR)

Amount of distillate water produced by solar-desalination system = 30 L/day (5 L/m^2/day)

Water required for crop irrigation according to peak crop coefficient ≈ 2.8 L/m^2/day

Area of land that can be irrigated by water produced by the system ≈ 11 m^2 (30/2.8)

Commercial greenhouse

Floor area = 360 m^2

Area of solar panel = 180 m^2 (30 panels)

System cost = panel cost + pumping cost

Cost of one 6-m^2 panel = 900 USD (3375.49 SAR)

System cost ≈ 27,000 USD (≈100,000 SAR)

Private (family) greenhouse

Floor area = 32 m^2

Area of solar panel = 16 m^2 (3 panels)

System cost ≈ 3500 USD (≈13,000 SAR)

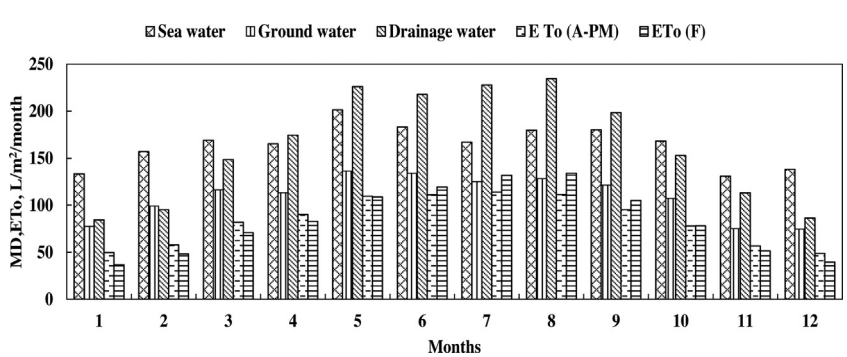

Fig. 9. The monthly values of productivity capacity (MD) of the different types of water and reference evapotranspiration (*ETo*) of adapted Penman-Monteith (A-PM) and Fernandez (F) methods.

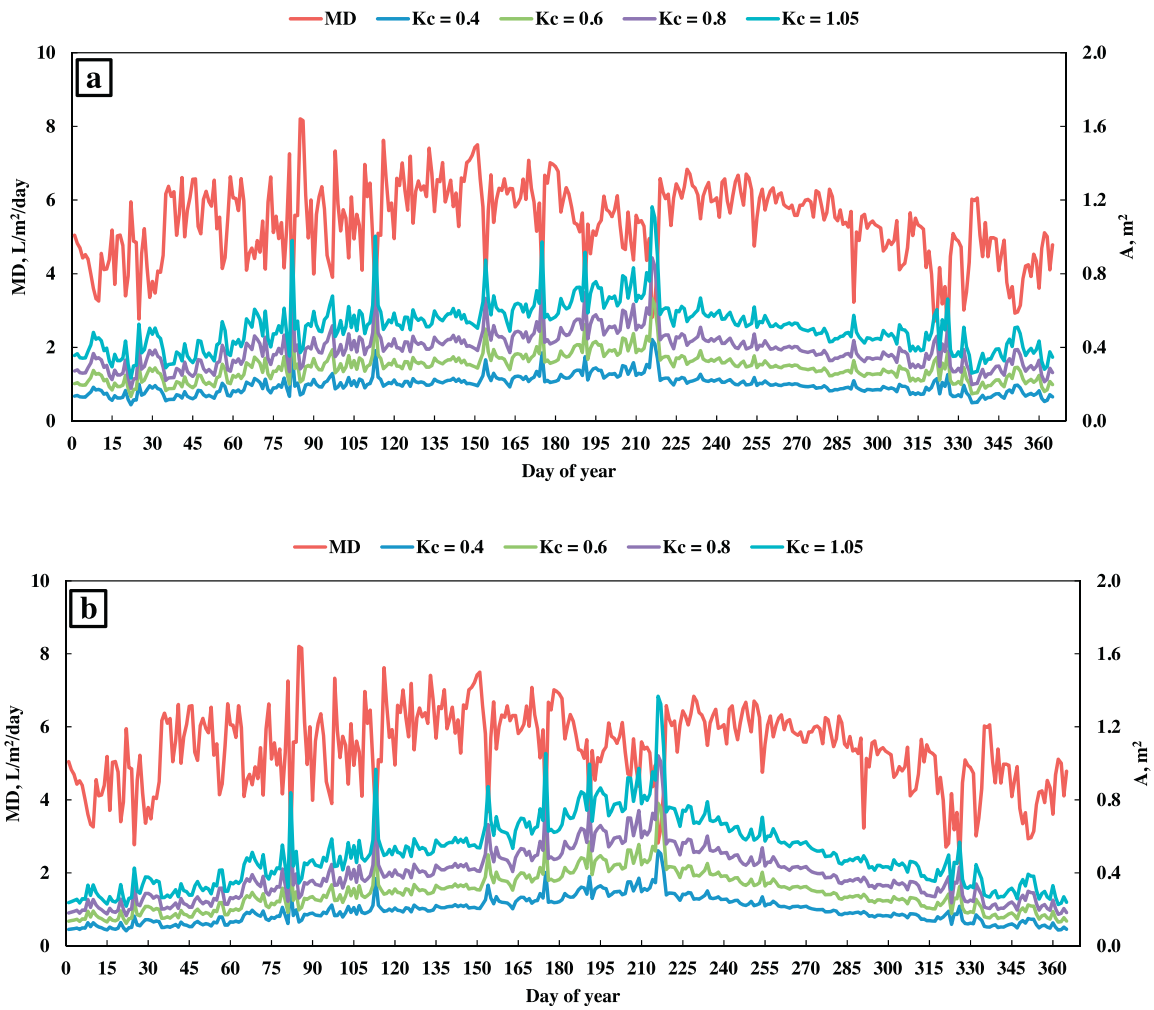

Fig. 10. Productivity capacity (MD) and area of the solar desalination system (*A*) using sea water and different crop coefficients (*Kc*) throughout the year with (a) adapted Penman-Monteith method and (b) Fernandez method.

Table 4
Comparison of CWR methods using numerical example with sea water, ground water and agricultural drainage water for one day (19 May).

MD (L/m²/day)	A-PM					F				
	ETo (mm/day)	*Kc*	*ETc* (mm/day)	CWR (mm/day)	*A* (m²)	*ETo* (mm/day)	*Kc*	*ETc* (mm/day)	CWR (mm/day)	*A* (m²)
Sea water										
5.95	3.35	0.4	1.34	1.28	0.22	3.31	0.4	1.32	1.27	0.21
	3.35	0.6	2.01	1.93	0.32	3.31	0.6	1.99	1.90	0.32
	3.35	0.8	2.68	2.57	0.43	3.31	0.8	2.65	2.54	0.43
	3.35	1.05	3.52	3.37	0.57	3.31	1.05	3.48	3.33	0.56
Ground water										
3.95	3.35	0.4	1.34	1.28	0.32	3.31	0.4	1.32	1.27	0.32
	3.35	0.6	2.01	1.93	0.49	3.31	0.6	1.99	1.90	0.48
	3.35	0.8	2.68	2.57	0.65	3.31	0.8	2.65	2.54	0.64
	3.35	1.05	3.52	3.37	0.85	3.31	1.05	3.48	3.33	0.84
Agricultural drainage water										
6.92	3.35	0.4	1.34	1.28	0.19	3.31	0.4	1.32	1.27	0.18
	3.35	0.6	2.01	1.93	0.28	3.31	0.6	1.99	1.90	0.28
	3.35	0.8	2.68	2.57	0.37	3.31	0.8	2.65	2.54	0.37
	3.35	1.05	3.52	3.37	0.49	3.31	1.05	3.48	3.33	0.48

4. Conclusion

New and effective means of supplying fresh water for greenhouse irrigation are urgently required. The outcomes of this study support the hypothesis that solar desalination is technically efficient and capable of meeting CWR in greenhouses. In this study, seawater, ground water and agricultural-drainage water underwent desalination. Three statistical models were derived from the experimental results and used to predict the annual MD of the solar-desalination system for each of the three types of water. *Rs* and UVI were found to have the greatest influence on MD. Rainfall and cloud cover were also found to have very negative effects on MD. Two methods were used to compute CWR: the *A-PM* method and the F method. The results were highly consistent.

The A-PM method was found to be an effective way of computing CWR. Generally, the average area of the solar-desalination system required to meet CWR using the A-PM method was greater than that using the F method, but the difference was small. MD was found to be largely unaffected by water type. The findings indicate that the MD of the system exceeded CWR for all types of water throughout the year. Therefore, the system appears to be capable of meeting CWR in greenhouses. It was also found that the water produced by 1 m^2 of the solar-still met the CWR of approximately 2 m^2 of greenhouse. More research should be conducted to examine the effects on crop yield of using the proposed system for irrigation. Collectively, the findings of this study suggest that solar desalination has the potential to provide a new irrigation-water resource capable of contributing to the sustainability and development of protected cultivation in greenhouses in arid, coastal and remote areas. To optimize the benefits of the solar-desalination system, the environmental conditions of the greenhouse cultivation system should be fully controlled; confined mulching, hydroponics or aeroponics should be implemented; and the most modern irrigation techniques should be used to minimize water loss.

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